Measurements of the $pp \to W\gamma\gamma$ and $pp \to Z\gamma\gamma$ cross sections and limits on anomalous quartic gauge couplings at $\sqrt{s} = 8$TeV

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DOI: https://doi.org/10.1007/JHEP10(2017)072

Originally published at:
CMS Collaboration; Canelli, Maria Florencia; Kilminster, Benjamin; Aarrestad, Thea K; Caminada, Lea; de Cosa, Annapaoloa; Del Burgo, Riccardo; Donato, Silvio; Galloni, Camilla; Hinzmann, Andreas; Hreus, Tomas; Ngadiuba, Jennifer; Pinna, Deborah; Rauco, Giorgia; Robmann, Peter; Salerno, Daniel; Schweiger, Korbinian; Seitz, Claudia; Takahashi, Yuta; Zucchetta, Alberto; et al (2017). Measurements of the $pp \to W\gamma\gamma$ and $pp \to Z\gamma\gamma$ cross sections and limits on anomalous quartic gauge couplings at $\sqrt{s}$ = 8TeV. Journal of High Energy Physics, 10:072.
DOI: https://doi.org/10.1007/JHEP10(2017)072

Published for SISSA by Springer

Received: April 2, 2017
Revised: July 13, 2017
Accepted: September 20, 2017
Published: October 11, 2017

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Keywords: Hadron-Hadron scattering (experiments)

ArXiv ePrint: 1704.00366

https://doi.org/10.1007/JHEP10(2017)072

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Contents

1 Introduction

Production of three-boson final states in proton-proton collisions is predicted by the SU(2)×U(1) gauge structure of the standard model (SM). Cross sections for these processes include contributions from quartic gauge couplings (QGCs), which are sensitive to new phenomena that modify those couplings. In this paper, we present cross section measurements for the pp $\to$ W$\gamma\gamma$ and pp $\to$ Z$\gamma\gamma$ processes and a search for anomalous QGCs (aQGCs). The W $\to \ell\nu$ and Z $\to \ell\ell$ decay modes are selected for analysis, where ℓ is a muon or an electron. The cross sections are measured in fiducial regions that are defined by selection criteria similar to those used to select signal events. In particular, to avoid infrared divergences, minimum photon transverse momenta p_{T} of 25 and 15 GeV are required in the W$\gamma\gamma$ and Z$\gamma\gamma$ measurements, respectively. A dimension-8 effective field theory is used to model aQGCs, which would enhance W$\gamma\gamma$ production at high momentum scales. The W$\gamma\gamma$ and Z$\gamma\gamma$ processes were recently observed by the ATLAS Collaboration [1, 2] using 20.3 fb^{-1} of integrated luminosity at $\sqrt{s} = 8$ TeV. Cross sections for W$\gamma\gamma$ and Z$\gamma\gamma$ production have also been computed with QCD corrections up to next-to-leading order (NLO) in refs. [3, 4].

2 The CMS detector and particle reconstruction

The data used in these measurements amount to 19.4 fb^{-1} collected in 2012 with the CMS detector at the CERN LHC in proton-proton collisions at a center-of-mass energy of 8 TeV. A detailed description of the CMS detector, together with definitions of the coordinate system and relevant kinematic variables, can be found in ref. [5]. The central feature of

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the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and plastic scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Extensive forward calorimetry utilizing a steel absorber with embedded quartz fibers complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The particle-flow (PF) algorithm [6] reconstructs and identifies five types of particles with an optimized combination of information from the various elements of the CMS detector. Particle flow candidates provide the basis for the selection and measurement of muons, electrons, photons, jets, and the transverse momentum imbalance. In addition, the isolation characteristics of identified leptons and photons are measured using the p_{T} of PF charged hadrons, neutral hadrons, and photons.

Muons are identified as tracks in the muon spectrometer that are matched to tracks in the inner detector. Quality requirements are placed on tracks measured in the inner detector and muon spectrometer, as well as on the matching between them. Muons must also be isolated from nearby PF candidates. Selected muons in the momentum range $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$ have a relative p_{T} resolution of 1.3–2.0% in the barrel ($|\eta| < 1.2$) and less than 6% in the endcaps ($1.2 < |\eta| < 2.4$) [7].

Photons and electrons are identified as clusters of energy deposits in the ECAL. The energy of photons is directly obtained from the ECAL measurement. Electrons are further identified by matching the ECAL cluster to a track reconstructed in the inner detector. The momenta of electrons are determined from a combination of the track momentum at the primary interaction vertex, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. To take into account electron bremsstrahlung in the inner-detector material, a Gaussian sum filter algorithm [8] is used to measure the track momentum. The momentum resolution for electrons from $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ decays ranges from 1.7% for electrons in the barrel region to 4.5% for electrons that begin to shower before the calorimeter in the endcaps [9].

Electrons are selected in the $\mathrm{W}\gamma\gamma$ analysis using a multivariate classifier based on the spatial distribution of the electron shower, the energy deposited in the HCAL region matched to the ECAL shower, and the quality of the inner-detector track. Electrons are selected in the $\mathrm{Z}\gamma\gamma$ analysis by imposing looser requirements on the same variables, yielding improved signal acceptance. In both cases, electrons passing the selection must also be isolated from nearby PF candidates.

Photons are identified using a selection that requires a narrow shower in the ECAL, minimal energy deposited in the HCAL region matched to the ECAL shower, and isolation from nearby PF candidates. Separate isolation requirements are placed on the energies of PF charged hadrons, neutral hadrons, and photons. Photons that convert to an electron-positron pair are included and the same selection criteria are applied. The energy resolution is about 1% in the barrel section of the ECAL for unconverted or late converting photons in the tens of GeV energy range. The remaining barrel photons have a resolution of about

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1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, which cover a pseudorapidity of $1.5 < |\eta| < 2.5$, the resolution of unconverted photons is about 2.5%, while converted photons have a resolution between 3 and 4% [10].

The transverse momentum imbalance vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the $\vec{p}_{\mathrm{T}}$ of all reconstructed PF candidates in the event. Its magnitude is referred to as $p_{\mathrm{T}}^{\mathrm{miss}}$. Corrections to the energy scale and resolution of jets, described in [11], are propagated to the calculation of $p_{\mathrm{T}}^{\mathrm{miss}}$.

3 Event selection

Events are recorded using single-lepton triggers for the $\mathrm{W}\gamma\gamma$ selection and dilepton triggers for the $\mathrm{Z}\gamma\gamma$ selection [12]. The single-lepton triggers have p_{T} thresholds of 24 and 27 GeV for muons and electrons, respectively. The dimuon and dielectron triggers both have p_{T} thresholds of 17 and 8 GeV on the leading and subleading leptons, respectively. To ensure uniform trigger efficiency, reconstructed leptons are required to have p_{T} above the trigger thresholds. The p_{T} requirement is determined by measuring the efficiency of the trigger as a function of p_{T} and selecting the value at which the efficiency becomes approximately independent of p_{T}. For the $\mathrm{W}\gamma\gamma$ ($\mathrm{Z}\gamma\gamma$) analysis the muons and electrons must have minimum p_{T} of 25 (10) and 30 (20) GeV, respectively.

Events selected for the $\mathrm{W}\gamma\gamma$ analysis must have one muon or electron and two photons. Each photon is required to have p_{T} greater than 25 GeV. Events are removed if a second lepton is present having p_{T} above 10 GeV. All reconstructed leptons and photons must be separated from each other by $\Delta R > 0.4$, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and ϕ is the azimuthal angle. To identify leptonic W boson decays and remove backgrounds not having genuine $p_{\mathrm{T}}^{\mathrm{miss}}$, the transverse mass, defined as

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos[\phi(\vec{p}_{\mathrm{T}}^{\ell}) - \phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}})])},$$

is required to be greater than 40 GeV; p_{T}^{ℓ} denotes the p_{T} of the lepton. In the electron channel, additional criteria are imposed to reject background events arising from Z boson decays to electrons in which only one electron is correctly identified, the other is misidentified as a photon, and an additional prompt photon is present in the event. Both photons are required to pass an electron veto that rejects photons that match to tracks in the pixel detector. This requirement decreases the signal efficiency by removing converted photons, which are commonly matched to tracks in the pixel detector. However, the background contamination from electrons is further decreased by a factor of two. Events are also removed if the invariant mass of any combination of the electron and one or both photons is near the Z boson mass. In particular, events are removed if they have $86 < m_{\mathrm{e}\gamma} < 96$ GeV for either combination of a photon with the electron, or if $86 < m_{\mathrm{e}\gamma\gamma} < 96$ GeV, in which case one photon is likely to be from final-state radiation (FSR).

Events selected for the $\mathrm{Z}\gamma\gamma$ analysis must have two electrons or muons of opposite charge and two photons. Each photon is required to have a minimum p_{T} of 15 GeV. Photons are required to pass an electron veto that has a higher signal efficiency than that used in the electron channel of the W$\gamma\gamma$ analysis. All reconstructed leptons and photons must be separated from each other by $\Delta R > 0.4$. The dilepton invariant mass must be greater than 40 GeV to remove backgrounds that have low dilepton invariant masses.

In both analyses, photons reconstructed in the barrel and endcaps are treated separately. The geometry of the ECAL differs between the barrel and endcaps and therefore different selection criteria are imposed for each case. Photons that are reconstructed in the endcaps are more likely to originate from misidentified jets. Events in which both reconstructed photons are in the endcaps are not considered in the analysis because of the unfavorable signal-to-background ratio.

4 Signal and background simulation

Simulated events are generated at NLO for the W$\gamma\gamma$ and Z$\gamma\gamma$ signals. These samples are generated with MadGraph5_aMC@NLO (v5 2.2.2) [13] using the NNPDF-NLO (v.3.0) [14] parton distribution functions (PDFs), and showered with PYTHIA (v.8.1) [15] using the Monash tune [16].

Events are generated that model the aQGC signals and the diboson and triboson backgrounds at leading order (LO) using MadGraph (v5 2.2.2) using the CTEQ6L1 [17] PDF set, and then showered with PYTHIA (v.6.4) [18] Z2* tune [19].

Simulated aQGC events are assigned a set of weights, each of which reproduces the effect of an anomalous QGC. The weights are obtained by loading models of effective theories, provided in the Universal FeynRules Output format [20], into the event generator. The diboson and triboson predictions are normalized to the NLO cross section predictions obtained with MCFM (v.6.6) [21] and MadGraph5_aMC@NLO (v5 2.2.2), respectively. All τ leptons included in samples showered with PYTHIA are decayed with TAUOLA (v.1.1.1a) [22].

The influence of additional proton-proton collisions in data events (pileup) is corrected by adding minimum-bias collisions to the simulated events. The number of added pileup collisions follows a distribution that is similar to the distribution observed in data and an additional weight is applied such that the simulated pileup distribution accurately represents the data. Finally, all simulated samples are passed through a detailed Geant4 simulation [23] of the CMS detector.

Corrections for differences between the simulation and the data in the selection efficiencies of muons, electrons, and photons and in the trigger efficiencies are determined using the tag-and-probe method and applied to the simulated events. Differences in the momentum scale of muons, electrons, and photons are determined from the Z boson line shape, and the simulation is corrected to agree with the data.

5 Background estimation

The main background contribution in both analyses consists of events in which one or two jets are misidentified as photons. In fact, while the photon shower and isolation requirements are designed to reject misidentified jets, the relatively large production rate of electroweak bosons with jets leads to a large contribution of jets misidentified as photons.

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A jet is commonly misidentified as a photon when it contains a neutral meson that decays to overlapping photons. If the photons carry a large fraction of the jet energy such that the other hadronization products have low momentum, the reconstructed photon can pass the isolation requirements. The probability for a jet to be misidentified as a photon is sensitive to how jets interact with the detector and is therefore difficult to predict with simulation. Moreover, the generation of a sufficiently large simulated sample is impractical because of the large rejection factor obtained through the photon identification criteria. A data-based method is therefore used to estimate the contamination from this source.

The background estimate is based on an analysis of the two-dimensional distribution of the charged hadron isolation variables $I_{\mathrm{ch},1}$ and $I_{\mathrm{ch},2}$ of the leading and subleading photon candidates, respectively. The isolation I_{ch} is defined as the scalar p_{T} sum of charged hadron PF candidates having $\Delta R < 0.3$ with respect to the photon candidate. Charged hadron PF candidates are required to have energy deposits in the HCAL and originate from the primary vertex, defined as the vertex with the highest sum of squared transverse momenta of its associated tracks [24]. Prompt photons have low values of I_{ch} while jets that are misidentified as photons tend to have larger values. The distribution of $I_{\mathrm{ch},1}$ versus $I_{\mathrm{ch},2}$ (a "template") is determined for each of the four sources of diphoton candidates: prompt-prompt (PP), prompt-jet (PJ), jet-prompt (JP), and jet-jet (JJ). The PP template represents the signal, while the PJ and JP templates represent background events having one prompt photon, and the JJ template represents background events having no prompt photons. Each template consists of four bins. The distribution of I_{ch} is divided into a "tight" region and a "loose" control region for each of the two photons. The tight region contains photon candidates that satisfy the nominal I_{ch} criterion, while the loose region contains photon candidates that fail the nominal, but pass a less stringent requirement. The value of the less stringent requirement is chosen such that candidates in the loose region are enriched in photon-like jets that are independent of, but sufficiently similar to those that contaminate the signal region. The four-bin structure of the templates provides discrimination between prompt photons and jets and allows for a straightforward matrix equation solution, taking account of correlations between $I_{\mathrm{ch},1}$ and $I_{\mathrm{ch},2}$. The contribution of each source is determined from control data samples. Three control data samples are formed from the combinations of the tight and loose regions: tight-loose (TL) and loose-tight (LT), where one photon passes the requirement and the other fails, and loose-loose (LL), where both photons fail the requirement. The signal region is labeled tight-tight (TT). The TL and LT regions are treated separately to take into account differences in photon p_{T} and differences between photons that are reconstructed in the barrel and endcaps. The normalizations of the four sources of photon candidates are determined through the matrix equation

$$\begin{pmatrix} N_{\mathrm{TT}} \\ N_{\mathrm{TL}} \\ N_{\mathrm{LT}} \\ N_{\mathrm{LL}} \end{pmatrix} = \begin{pmatrix} \epsilon^{\mathrm{TT}}_{\mathrm{PP}} & \epsilon^{\mathrm{TT}}_{\mathrm{PJ}} & \epsilon^{\mathrm{TT}}_{\mathrm{JP}} & \epsilon^{\mathrm{TT}}_{\mathrm{JJ}} \\ \epsilon^{\mathrm{TL}}_{\mathrm{PP}} & \epsilon^{\mathrm{TL}}_{\mathrm{PJ}} & \epsilon^{\mathrm{TL}}_{\mathrm{JP}} & \epsilon^{\mathrm{TL}}_{\mathrm{JJ}} \\ \epsilon^{\mathrm{LT}}_{\mathrm{PP}} & \epsilon^{\mathrm{LT}}_{\mathrm{PJ}} & \epsilon^{\mathrm{LT}}_{\mathrm{JP}} & \epsilon^{\mathrm{LT}}_{\mathrm{JJ}} \\ \epsilon^{\mathrm{LL}}_{\mathrm{PP}} & \epsilon^{\mathrm{LL}}_{\mathrm{PJ}} & \epsilon^{\mathrm{LL}}_{\mathrm{JP}} & \epsilon^{\mathrm{LL}}_{\mathrm{JJ}} \end{pmatrix} \begin{pmatrix} \alpha_{\mathrm{PP}} \\ \alpha_{\mathrm{PJ}} \\ \alpha_{\mathrm{JP}} \\ \alpha_{\mathrm{JJ}} \end{pmatrix}, \tag{5.1}$$

where N_{XY} is the observed number of events in region XY, ϵ_{AB}^{XY} is the probability for an event from source AB to appear in region XY, as determined from the templates, and α_{AB} is the normalization of source AB. Each column in the matrix corresponds to the four bins from one template, and the entries in the column sum to unity by construction. The predicted number of events from source AB reconstructed in region XY is given by the product $\alpha_{AB}\,\epsilon_{AB}^{XY}$. The final background estimate is the sum of the contributions from the sources involving at least one jet:

$$\alpha_{\mathrm{PJ}}\,\epsilon_{\mathrm{PJ}}^{\mathrm{TT}} + \alpha_{\mathrm{JP}}\,\epsilon_{\mathrm{JP}}^{\mathrm{TT}} + \alpha_{\mathrm{JJ}}\,\epsilon_{\mathrm{JJ}}^{\mathrm{TT}}.$$

Templates are constructed from both Monte Carlo (MC) simulation and data control samples. This procedure is applied separately for different ranges of photon p_{T} and η. The templates for the PP, PJ, and JP sources are determined from prompt and jet I_{ch} distributions obtained from single-photon events. The single-photon I_{ch} distributions are binned in the same manner as the templates to create two-bin distributions representing the leading and subleading photon. Products of the two-bin distributions corresponding to the leading and subleading photons are used to determine the four-bin templates, the entries of which appear in eq. (5.1).

The I_{ch} distribution for prompt photons is taken from simulated Wγ events. Simulated events are required to contain one reconstructed photon that matches a photon in the generator record within $\Delta R = 0.2$ and passes all selection criteria except the I_{ch} requirement. The distributions obtained from simulation are validated with data events in which an FSR photon is identified in a Z boson decay to $\mu^+\mu^-$. To ensure that the photon results from FSR, the three-body invariant mass is required to be consistent with the Z boson mass and the photon must be within $\Delta R = 1$ of a muon. The available data sample is adequate to make this comparison for photons with p_{T} up to 40 GeV, and good agreement is observed between data and simulation. An uncertainty of 10–20% is applied, depending on the photon p_{T} and η, to take into account the observed differences and for the extrapolation to higher photon p_{T}.

The I_{ch} distribution for jets is taken from data. For this purpose, events are selected that contain two reconstructed muons with invariant mass consistent with the Z boson mass and a reconstructed photon that passes all selection criteria except the I_{ch} requirement. To exclude genuine photons from FSR, the photon is required to be separated from each muon by $\Delta R > 1$. The remaining contribution from prompt photons is subtracted using the prediction from a sample of simulated Zγ events normalized to its production cross section calculated at next-to-next-to-leading order [25]. This normalization is checked with a control data sample similar to that used to validate the I_{ch} distribution for prompt photons. Based on this comparison, a systematic uncertainty of 20%, dominated by the statistical uncertainty in the control sample, is assessed to the Zγ normalization.

Events that have two jets misidentified as photons represent approximately 30% and 10% of the total misidentified jet background in the W$\gamma\gamma$ and Z$\gamma\gamma$ analyses, respectively. In such events, nonnegligible correlations exist between the leading and subleading photons. These correlations originate from the event activity that affects the measured isolation energies of both photons. The JJ templates are therefore determined from a sample of candidate diphoton events in data that is independent of the signal region. For this selection, the requirement on the ECAL transverse shower shape is inverted and the PF photon isolation requirement is relaxed. This procedure can result in a bias through correlations between the ECAL shower shape and the isolation. The systematic uncertainties are estimated by varying the maximum value of the relaxed requirements on the PF photon isolation. The largest deviation is taken as an estimate of the systematic uncertainty, which is approximately 10%. Using this method, rather than treating the photons as uncorrelated, increases the contribution from jet-jet events, which increases the estimated background by as much as 30%.

The total uncertainties in the estimated background contamination from misidentified jets are 19% and 28% for the muon and electron $W\gamma\gamma$ channels, respectively, and 14% for the muon and electron $Z\gamma\gamma$ channels. These uncertainties take into account systematic effects in the derivation of the probabilities for prompt photons and jets described above, and statistical uncertainties in the observed data. The larger uncertainty in the electron channel of the $W\gamma\gamma$ analysis results from the smaller amount of data as well as larger systematic variations in the JJ template determination.

In the electron channel of the $W\gamma\gamma$ analysis, a nonnegligible contamination is present from $Z(\to ee)\gamma$ events in which an electron is misidentified as a photon. An electron veto based on pixel tracks is used as a discriminating variable to determine a misidentification ratio. This ratio relates the number of events that fail the electron veto to the number that pass. The misidentification ratio is determined as a function of p_T and η in a control sample of data enriched in single Z boson events that have one reconstructed electron and one photon. The contamination in the signal region is obtained by multiplying the observed number of events outside the Z boson mass window where one photon fails the electron veto by the misidentification ratio. The number of electrons resulting from Z boson decays is extracted from a fit to the $e\gamma$ invariant mass distribution using a Z boson line shape determined from simulation and a background function that models the contribution from events without a Z boson. The misidentification ratio is 0.01–0.03, depending on the p_T and η of the photon. A systematic uncertainty of 10% in the misidentification ratio is determined from a closure test in simulation. The contamination from misidentified jets in the control samples is determined using the method described above and subtracted from the data. This contamination is approximately 10% for events in which both photons are in the barrel and 20% for the remaining events.

Additional background contributions involving prompt photons are determined using MC simulations. The simulated events are corrected for observed differences in the selection efficiencies between data and simulation of electrons, muons, and photons and in the trigger efficiencies. In the $W\gamma\gamma$ analysis, the contamination from $Z\gamma\gamma$ is estimated using the $Z\gamma\gamma$ MC sample described in section 4. The $Z\gamma\gamma$ contamination constitutes about 90% of the background that contains two prompt photons. The simulated sample is normalized to the NLO cross section with an uncertainty of 12.5%, based on the uncertainty in the theoretical prediction and differences in identification and reconstruction efficiencies between data and simulation. Contributions of less than an event per channel from top quark production and other multiboson processes, including $t\bar{t}\gamma\gamma$, $tW\gamma\gamma$, and $VV\gamma\gamma$, where V is a W or Z boson,

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$W\gamma\gamma$	Electron channel	Muon channel
Jet $\to \gamma$ misidentification	22 ± 6	63 ± 12
Electron $\to \gamma$ misidentification	20 ± 2	—
Prompt diphoton	7 ± 1	14 ± 2
Total background	49 ± 6	77 ± 12
Expected signal	13 ± 1	25 ± 3
Data	63	108
$Z\gamma\gamma$	Electron channel	Muon channel
Jet $\to \gamma$ misidentification	62 ± 8	68 ± 9
Prompt diphoton	0.3 ± 0.1	0.6 ± 0.2
Total background	62 ± 8	69 ± 9
Expected signal	56 ± 8	73 ± 10
Data	117	141

Table 1. Background composition, expected signal, and observed yields in the $W\gamma\gamma$ (upper) and $Z\gamma\gamma$ (lower) analyses.

are present in both the $W\gamma\gamma$ and $Z\gamma\gamma$ final states. These background sources are estimated using leading-order MC simulation. A systematic uncertainty of 20% is applied to the sum of these contributions to take into account higher-order corrections and differences in identification and reconstruction efficiencies between data and simulation.

Table 1 summarizes the background predictions and the observed numbers of events, which are consistent with the presence of signal. Figure 1 shows the diphoton p_T distribution with the predicted background, signal, and observed data for the $W\gamma\gamma$ and $Z\gamma\gamma$ analyses, separately in the electron and muon channels. Figure 2 shows the same distributions with the electron and muon channels combined. The $W\gamma\gamma$ and $Z\gamma\gamma$ signals are observed with significances of 2.6 and 5.9 standard deviations, respectively. The significances of the signals are calculated using a profile likelihood that considers the observed data and predicted backgrounds in each of the muon and electron channels. In this calculation, separate categories are defined for events having both photons in the barrel and only one photon in the barrel, to take advantage of the higher signal-to-background ratio in the first category as compared to the second.

6 Cross section measurements

The $W\gamma\gamma$ and $Z\gamma\gamma$ cross sections are measured within fiducial regions identified by the selection criteria listed in table 2. The acceptances of the fiducial regions for the signal processes as well as their reconstruction and selection efficiencies are determined using the signal MC samples described in section 4. In the MC simulation, photons are required to satisfy a Frixione isolation requirement with a distance parameter of 0.05 [26]. The fiducial selection criteria are applied to the generated lepton four-momenta after a correction for FSR, which is obtained by adding to the generated four-momentum of each lepton the

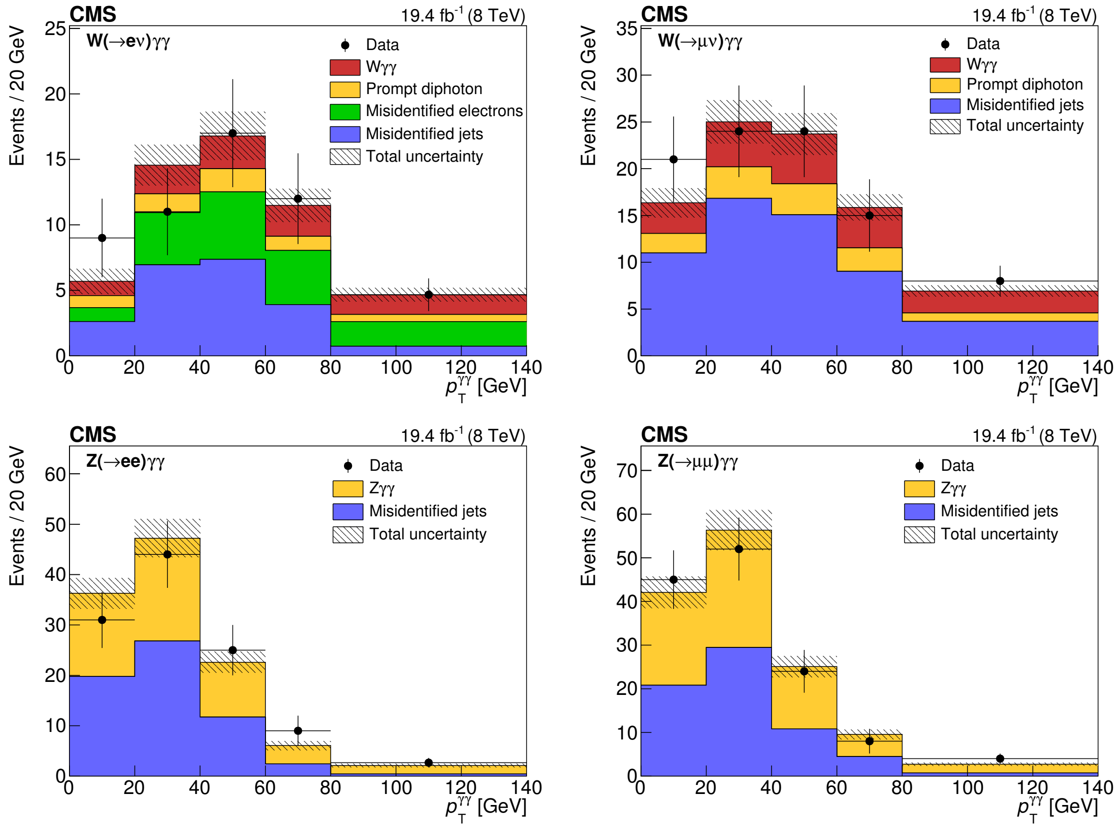

Figure 1. Distributions of the diphoton p_{T} for the W$\gamma\gamma$ (upper) and Z$\gamma\gamma$ (lower) analyses, in the electron (left) and muon (right) channels. The points display the observed data and the histograms show the predictions for the background and signal. The indicated uncertainties in the data points are calculated using Poisson statistics. The hatched area displays the total uncertainty in the sum of these predictions. The predictions for electrons and jets misidentified as photons are obtained with data-based methods. The remaining background and signal predictions are derived from MC simulation. The last bin includes all events in which the diphoton p_{T} exceeds 80 GeV.

generated four-momenta of all photons within $\Delta R < 0.1$. The fiducial cross sections are defined for W and Z boson decays to a single lepton family (ℓ).

Leptonic decays of τ leptons resulting from W and Z decays also contribute to signal events. Based on simulation the τ lepton contamination in the W$\gamma\gamma$ fiducial region is approximately 2.5%, while in the Z$\gamma\gamma$ fiducial region it is less than 1%. The combined acceptances and efficiencies, after subtracting the τ lepton contribution, are 17.3 and 26.7% for the electron and muon channels of the W$\gamma\gamma$ analysis, respectively, and 22.5 and 29.1% for the Z$\gamma\gamma$ analysis.

Uncertainties in the acceptances result from uncertainties in the PDFs of the proton, the perturbative QCD renormalization and factorization scales, the number of additional pileup interactions, and the selection efficiencies of leptons, photons, and $p_{\mathrm{T}}^{\mathrm{miss}}$. The PDF uncertainties are evaluated by comparing the acceptances obtained with the NNPDF-NLO error sets and between the nominal NNPDF-NLO set and the MSTW-NLO 2008 [27] and

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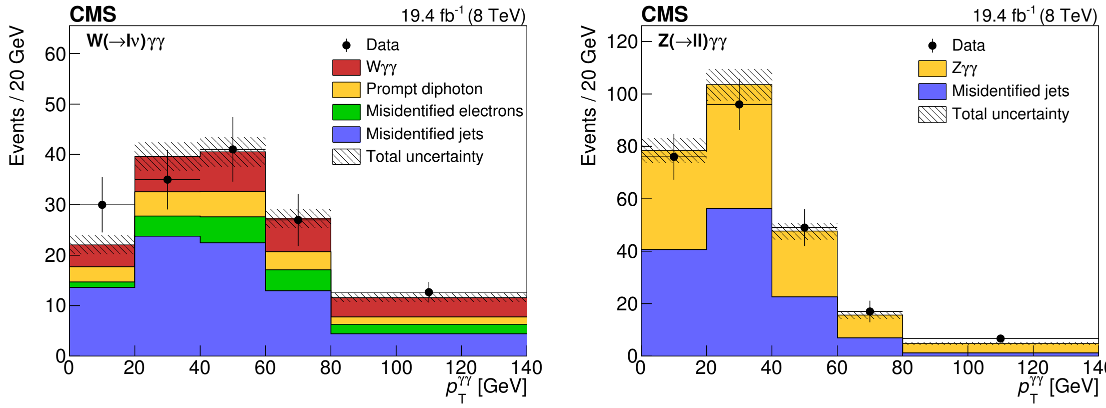

Figure 2. Distributions of the diphoton p_{T} for the W$\gamma\gamma$ (left) and Z$\gamma\gamma$ (right) analyses with the electron and muon channels summed. The points display the observed data and the histograms give the predictions for the background and signal. The indicated uncertainties in the data points are calculated using Poisson statistics. The hatched area displays the total uncertainty in the sum of these predictions. The predictions for electrons and jets misidentified as photons are obtained with data-based methods. The remaining background and signal predictions are derived from MC simulation. The last bin includes all events in which the diphoton p_{T} exceeds 80 GeV.

CT10-NLO [28] PDF sets. The maximum deviation from the nominal acceptance is taken as a systematic uncertainty. The uncertainties related to the renormalization and factorization scales are evaluated by varying them independently by factors of 0.5 and 2. The largest variation is applied as a systematic uncertainty. The uncertainty in the pileup distribution is evaluated by varying the assumed minimum-bias cross section by $\pm5\%$. Uncertainties in the selection efficiencies of electrons, muons, and photons and in the trigger requirements are derived from uncertainties in the tag-and-probe analyses. Estimates of the energy scale uncertainty for the electron, photon, and muon are made from comparisons of the Z boson line shape between data and simulation. Uncertainties in the $p_{\mathrm{T}}^{\mathrm{miss}}$ energy scale are estimated by propagating the energy scale uncertainty for each object used in the $p_{\mathrm{T}}^{\mathrm{miss}}$ calculation. The total uncertainties in the combined acceptances and efficiencies are 1–2%. The integrated luminosity used for these measurements is 19.4 fb^{-1} with an uncertainty of 2.6% [29]. A summary of the systematic uncertainties affecting the W$\gamma\gamma$ and Z$\gamma\gamma$ fiducial cross section measurements is reported in table 3.

The cross sections measured in the electron and muon channels of each analysis are combined, assuming lepton universality, using the method of best linear unbiased estimates [30–32], thereby decreasing the statistical uncertainties. We measure fiducial cross sections of $4.9 \pm 1.4\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst}) \pm 0.1\,(\mathrm{lumi})$ fb and $12.7 \pm 1.4\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})$ fb for the W$\gamma\gamma$ and Z$\gamma\gamma$ processes, respectively. The measured cross sections are in agreement with the NLO theoretical predictions of 4.8 ± 0.5 fb and 13.0 ± 1.5 fb for the W$\gamma\gamma$ and Z$\gamma\gamma$ final states, respectively. The predicted cross sections are calculated within the fiducial phase space given in table 2 using MadGraph5_aMC@NLO. Table 4 summarizes these results.

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Definition of the W$\gamma\gamma$ fiducial region
$p_{\mathrm{T}}^{\gamma} > 25\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{\mathrm{T}}^{\ell} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.4$
One candidate lepton and two candidate photons
$m_{\mathrm{T}} > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$
Definition of the Z$\gamma\gamma$ fiducial region
$p_{\mathrm{T}}^{\gamma} > 15\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_{\mathrm{T}}^{\ell} > 10\,\mathrm{GeV}$, $\lvert\eta^{\ell}\rvert < 2.4$
Two oppositely charged candidate leptons and two candidate photons
leading $p_{\mathrm{T}}^{\ell} > 20\,\mathrm{GeV}$
$m_{\ell\ell} > 40\,\mathrm{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$

Table 2. Fiducial region definitions for the W$\gamma\gamma$ analysis (upper) and Z$\gamma\gamma$ analysis (lower). The transverse mass m_{T} is defined as in the event selection, but with $p_{\mathrm{T}}^{\mathrm{miss}}$ replaced by the neutrino transverse momentum.

	W$\gamma\gamma$		Z$\gamma\gamma$	
	e channel	μ channel	ee channel	$\mu\mu$ channel
Systematic uncertainties associated with the simulation				
Simulation statistical uncertainty	2.8	2.4	3.3	2.9
Trigger	0.5	0.3	1.3	1.2
Lepton and photon ID and energy scale	4.1	3.0	5.3	4.3
$p_{\mathrm{T}}^{\mathrm{miss}}$ scale	1.5	1.4	—	—
Pileup	0.5	0.2	1.3	0.4
PDFs, renorm. and fact. scales	1.5	1.6	1.2	1.3
Systematic uncertainties associated with backgrounds				
Misidentified jet	36.6	37.2	15.1	12.5
Misidentified electron	6.9	—	—	—
Prompt diphoton	6.7	5.8	0.2	0.3
Summary				
Total statistical	47.8	29.6	16.6	13.7
Total systematic	38.3	37.9	16.5	13.7
Integrated luminosity	2.6	2.6	2.6	2.6

Table 3. Systematic and statistical uncertainties affecting the W$\gamma\gamma$ and Z$\gamma\gamma$ fiducial cross section measurements, presented as percentages of the measured cross section.

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Channel	Measured fiducial cross section
$W\gamma\gamma \to e^{\pm}\nu\gamma\gamma$	$4.2 \pm 2.0\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})\,\text{fb}$
$W\gamma\gamma \to \mu^{\pm}\nu\gamma\gamma$	$6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})\,\text{fb}$
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.9 \pm 1.4\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})\,\text{fb}$
$Z\gamma\gamma \to e^{+}e^{-}\gamma\gamma$	$12.5 \pm 2.1\,(\text{stat}) \pm 2.1\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb}$
$Z\gamma\gamma \to \mu^{+}\mu^{-}\gamma\gamma$	$12.8 \pm 1.8\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb}$
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	$12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb}$
Channel	Prediction
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.8 \pm 0.5\,\text{fb}$
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	$13.0 \pm 1.5\,\text{fb}$

Table 4. Measured fiducial cross section for each channel and for the combination of channels for the $W\gamma\gamma$ and $Z\gamma\gamma$ analyses. The combined cross sections assume lepton universality and are given for the decay to a single lepton family (ℓ). The predictions are reported as well.

7 Limits on aQGCs

Anomalous QGCs are modeled using a dimension-8 effective field theory parametrization [33]. The effective field theory extends the SM Lagrangian to terms of dimension larger than four. Each additional dimension is suppressed by a power of the energy scale Λ at which the new phenomena appear. The terms in the extended Lagrangian having odd-numbered dimensionality lead to baryon and lepton number violation and are therefore not considered here. The dimension-8 term is then the lowest-dimension term that produces aQGCs. Fourteen dimension-8 operators contribute to the $WW\gamma\gamma$ vertex [34, 35]. We focus our study on the couplings that contain products of electroweak field strength tensors, in particular those that are constrained by this analysis: $f_{M,2}$, $f_{M,3}$, $f_{T,0}$, $f_{T,1}$, and $f_{T,2}$ [36]. Anomalous QGCs enhance the production of signal events at high momentum scales. To increase sensitivity to these enhancements, limits on aQGCs are obtained using only events in which the leading-photon p_T exceeds 70 GeV. Figure 3 shows the predicted yield from an aQGC with $f_{T,0}/\Lambda^4 = 50\,\text{TeV}^{-4}$, compared to the signal and background predictions for the sum of the electron and muon channels. A profile likelihood is used to establish 95% confidence level (CL) intervals for the aQGC parameters. Each coupling is profiled individually, with the other couplings set to their SM values. Since all couplings predict an excess of the data at large photon p_T, the observed limits are larger than the expected limits for all couplings. The resulting limits are reported in table 5.

8 Summary

Cross sections have been measured for $W\gamma\gamma$ and $Z\gamma\gamma$ production in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ using data corresponding to an integrated luminosity of $19.4\,\text{fb}^{-1}$ collected with the CMS experiment. The cross sections were measured in fiducial regions that are defined by criteria similar to those used to select signal events. The fiducial cross sections

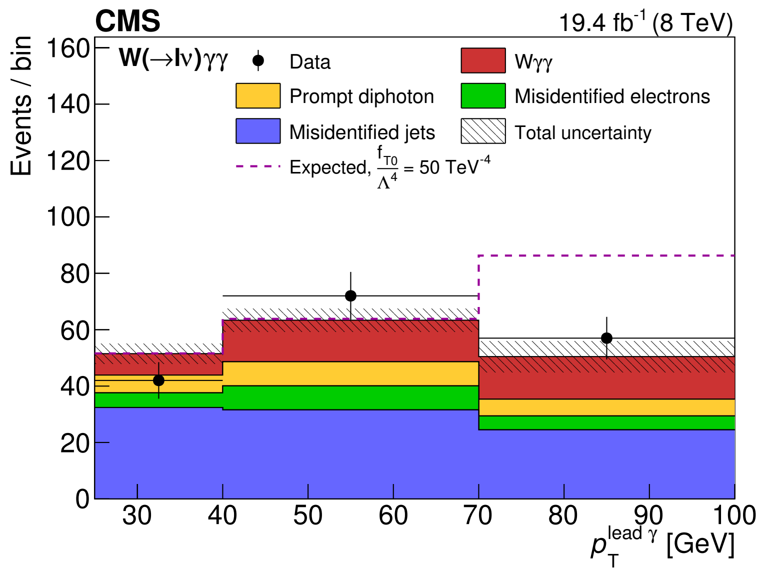

Figure 3. Distributions of the leading photon p_{T} for the W$\gamma\gamma$ analysis with the electron and muon channels summed. The points display the observed data and the histograms give the predictions for the background and signal. The indicated uncertainties in the data points are calculated using Poisson statistics. The hatched area displays the total uncertainty in the sum of these predictions. The expected distribution with the inclusion of an aQGC with $f_{\mathrm{T},0}/\Lambda^4 = 50\,\mathrm{TeV}^{-4}$ is shown as the dashed line. The last bin includes all events in which the leading photon p_{T} exceeds 70 GeV.

W$\gamma\gamma$	Expected (TeV^{-4})	Observed (TeV^{-4})
$f_{\mathrm{M},2}/\Lambda^4$	$[-549, 531]$	$[-701, 683]$
$f_{\mathrm{M},3}/\Lambda^4$	$[-916, 950]$	$[-1170, 1220]$
$f_{\mathrm{T},0}/\Lambda^4$	$[-26.5, 27.0]$	$[-33.5, 34.0]$
$f_{\mathrm{T},1}/\Lambda^4$	$[-34.5, 34.8]$	$[-44.3, 44.8]$
$f_{\mathrm{T},2}/\Lambda^4$	$[-74.6, 73.7]$	$[-93.8, 93.2]$

Table 5. Expected and observed 95% CL limits on anomalous quartic gauge couplings. Limits are obtained using W$\gamma\gamma$ events in which the leading photon p_{T} exceeds 70 GeV.

are defined for W and Z boson decays to a single lepton family. The measured fiducial cross sections for these final states are, respectively, 4.9 ± 2.1 fb and 12.7 ± 2.3 fb, consistent with the NLO theoretical predictions of 4.8 ± 0.5 fb and 13.0 ± 1.5 fb. These measurements correspond to significances for observing the signal of 2.6 and 5.9 standard deviations for the W$\gamma\gamma$ and Z$\gamma\gamma$ final states, respectively. In comparison, the ATLAS experiment measured the W$\gamma\gamma$ and Z$\gamma\gamma$ final states with significances of greater than three standard deviations and equal to 6.3 standard deviations, respectively [1, 2]. The W$\gamma\gamma$ final state is used to place limits at 95% CL on anomalous quartic gauge couplings using a dimension-8 effective field theory. In particular, stringent limits are placed on the $f_{\mathrm{T},0}$ coupling parameter of $-33.5 < f_{\mathrm{T},0}/\Lambda^4 < 34.0\,\mathrm{TeV}^{-4}$.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonatabis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

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20: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at Institute of Physics, Bhubaneswar, India
23: Also at University of Ruhuna, Matara, Sri Lanka
24: Also at Isfahan University of Technology, Isfahan, Iran
25: Also at Yazd University, Yazd, Iran
26: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
27: Also at Università degli Studi di Siena, Siena, Italy
28: Also at Purdue University, West Lafayette, U.S.A.
29: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
30: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
31: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
32: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
33: Also at Institute for Nuclear Research, Moscow, Russia
34: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
35: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
36: Also at University of Florida, Gainesville, U.S.A.
37: Also at P.N. Lebedev Physical Institute, Moscow, Russia
38: Also at California Institute of Technology, Pasadena, U.S.A.
39: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
41: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
42: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
44: Also at National and Kapodistrian University of Athens, Athens, Greece
45: Also at Riga Technical University, Riga, Latvia
46: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
47: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
48: Also at Istanbul Aydin University, Istanbul, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Cag University, Mersin, Turkey
51: Also at Piri Reis University, Istanbul, Turkey
52: Also at Gaziosmanpasa University, Tokat, Turkey

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53: Also at Adiyaman University, Adiyaman, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Yildiz Technical University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, U.S.A.
65: Also at BEYKENT UNIVERSITY, Istanbul, Turkey
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
68: Also at Texas A&M University at Qatar, Doha, Qatar
69: Also at Kyungpook National University, Daegu, Korea

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